Lightweight Bionic Robotic Arms Using Hoop-Reinforced Dielectric Elastomeric Actuators

Fa-Yi Chen, Tse-Han Lin, Chee-How Lu, Hao-Yan Wu, Shu Huang, and Gih-Keong Lau

***Abstract*—Artificial biceps based on rolled dielectric elastomer actuators were envisaged to drive a lightweight robotic arm but suffer from limited force generation. A long roll of the actuators has strain accumulated at the expenditure of reduced strength. Due to limited force generation, their applications regress to where low force is adequate. In this work, we reinforced a roll of the dielectric elastomer actuator (DEA) by multi-segment hoops of polyimide film to keep the DEA membrane in high pre-stretch and thus high dielectric strength. The multi-segment roll of 4-layered DEA with 5-times hoop pre-stretch and 4-times axial pre-stretch sustained a very high electric field of up 105MV/m. Such inactive DEA rolls each of 6.6-gram light and 115mm long supported a 500-gram payload. When activated between 4-5kV, the DEA roll can produce 24-25% elongation. In addition, the polyimide hoop reinforcement is much lighter than the metal helical coil used in the spring roll. Hence, the reinforced dielectric elastomer rolls achieved a 15.3J/kg high isotonic work density which is almost 4 to 5 times that achieved by a referenced spring roll. They made forceful biceps muscles with a payload capacity of half the mass of robotic arms. Further, the reinforced DEAs also made a bionic gripper with a payload capacity of 10 times the gripper weight. Multiplication of the bicipital muscle unit can help sustain an even higher payload.**

***Index Terms*—Bionic robotic arm, artificial muscles, dielectric elastomer actuators, soft grippers.**

I. Introduction

Lightweight low-duty robotic arms have recently gained popularity in the applications for safe machine interaction with a human [1,2]. With the latest development of a highly-geared motor of reduced weight, the immobile robotic arms can now run the chores of coffee making,, while mobile robotic arms can serve dishes [2]. Further, Disney researchers [3,4] developed a fluidic-driven robotic arm that delivered fluidic motion for playing a musical instrument like xylophone while interacting with kids. Due to the compliance, the fluidic-driven robotic arms are safe for use in human-robot interactions. The combined pneumatic and hydraulic drive deliver more speed and torque per unit weight (torque density) in comparison to the highly geared servos or motors[4]. However, they require heavy air compressors or pressure reservoirs and costly solenoid valves [5].

To date, motor-driven robotic arms are no match to the human arm which can perform both the fluidic and strong motion. For example, while an adult arm of 3kg mass can lift a dumbbell 3 to 5 times the arm weight, it can also perform fluidic swing for calligraphy writing. In comparison, a 'lightweight' robotic arm is not light with a highly geared motor drive and its payload capacity is limited. For example, the 22.3kg Kuka Robotics' LBR iiwa 7 R800 [6] can lift a payload of one-third of its total weight. The weight minimization of arm linkage is possible using carbon or glass fiber reinforced polymer. Alternatively, further weight minimization is possible by replacing copper-based electric motors with dielectric elastomer actuators, which feature high work density, i.e. output work per unit mass.

Why rubbery material stands a chance to make stronger artificial muscles? Rubber is lightweight material, but it can store a large amount of elastic potential energy when being highly stretched. For example, a rubber band catapult can eject a projectile fast and forcefully by releasing the stored elastic energy in a stretched rubber band. Calculation shows that the mass-specific elastic energy in a stretched rubber band can readily hit 1651 J/kg according to Ref. [7]. This suggests that the rubbery dielectric elastomer actuator stands a great potential for work. A dielectric elastomer actuator is a soft capacitor that deforms upon being squeezed by electrostatic pressure [8,9]. Recently electroactive polymer actuators show potential as artificial muscles to drive a lightweight and forceful robotic arm [9-12]. In the 2005 human-machine arm-wrestling match [10,13], an 20kg bionic robotic arm had used 250 rolls of dielectric elastomer actuators to arm wrestle against a 17-year-old girl but lost. Further development is necessary to make dielectric elastomer actuators stronger.

The force output of dielectric elastomer actuators is a direct result of maximum electrostatic pressure, which in turn depends on the dielectric strength. In the early development, the soft dielectric elastomer is subjected pre-mature dielectric breakdown and could not produce high electrostatic pressure for actuation. In an important discovery, Kofod [14] found stretching a foam tape biaxially for 3-5 times can greatly increase the dielectric strength of acrylic foam tape from 20MV/m to above 100MV/m and the electrostatic pressure comparable to the active stress in human muscles. This laid the foundation for strong artificial muscles. However, it is not easy to keep the pre-stretch in rubber material. An extra biasing spring is needed to stretch the dielectric elastomer membrane but introduces passive weight and thus reduces the overall work density. Pei et. al. [15,16] introduced a core of helical spring to the roll of dielectric elastomer membrane in high pre-stretch. Later, Huang et. al. [17] used multiple fiber hoops to keep the DEA roll in cylindrical shape but the hoop pre-stretch in DEA was avoided for fear of buckling the reinforcement fibers. While the reinforcement by metallic helical coil spring is stronger for hoop stretch than the nylon wire [11, 17], the hard coil can penetrate into the soft wound of the dielectric elastomer membrane [18-20]. This limits the roll DEA with the spring core be not activated beyond 80MV/m according to Ref. [10], even

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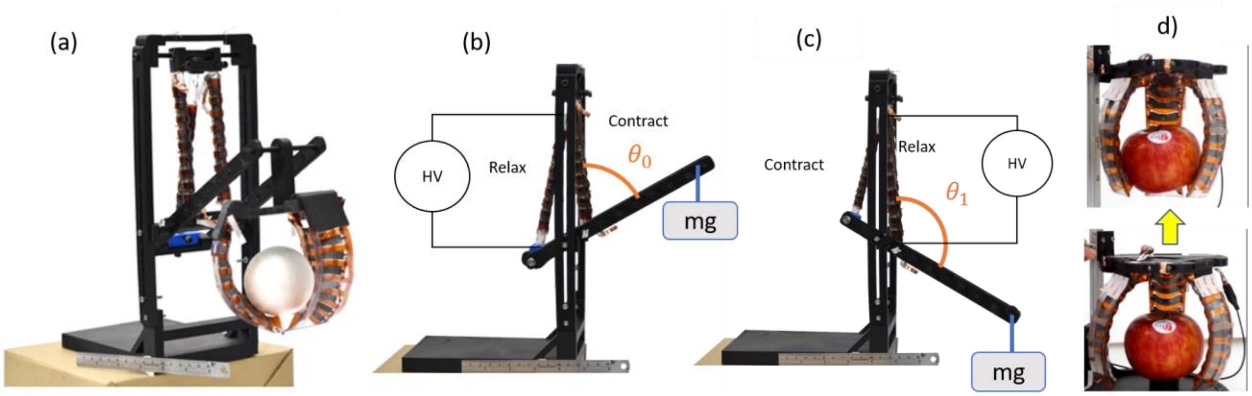


Fig. 1. Bionic design of robotic arm and grippers using dielectric elastomer actuators: (a) integrated arm and gripper; (b)-(c) arm flexion and extension by alternative activation of artificial biceps and triceps; (d) bionic grippers for apple grasping

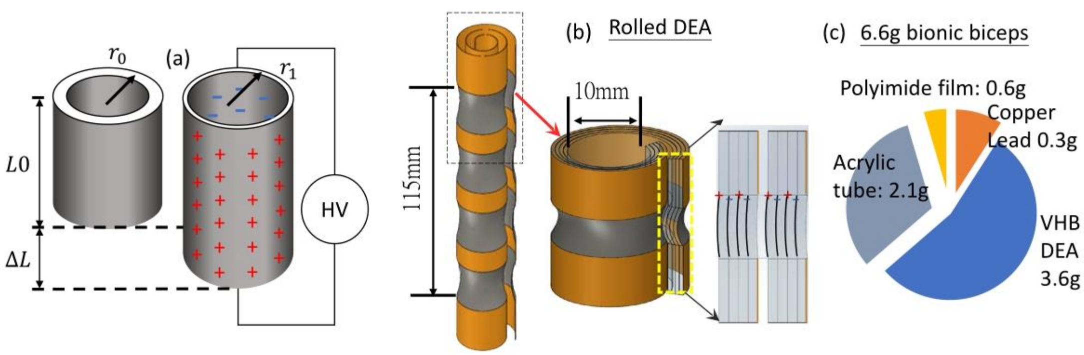


Fig. 2. (a) Actuation principle for a tubular dielectric elastomer actuator, (b) its application to a rolled dielectric elastomer actuator, (c) weight components

though a flat DEA can be activated between 100-150MV/m for high-stress actuation [12, 21].

Rolled dielectric elastomer actuators [16-18] were proposed and demonstrated as artificial biceps for driving lightweight robotic arms, but a long roll of the actuators has strain accumulation at the expenditure of reduced strength. In this paper, we proposed the multi-segmentation of a long DEA roll with hoop reinforcement by rolling up flat strips of polyimide film together with multi-layered dielectric elastomer actuators. These tubular segmentations are both lightweight and strong enough to keep the high hoop pre-stretch in the roll DEA. This will greatly increase the dielectric strength, actuation and work density. Subsequent results show this hoop-reinforced roll of DEA performs as well as biceps or triceps for driving a lightweight robotic arm. In addition, a lightweight bionic gripper based on DEA helps grasping an object up to ten times the grippers' weight.

II. BIONIC ROBOTIC ARM DESIGN

The concept and development of a bionic arm using rolled dielectric elastomer actuator was not new. But, the demonstration of using a highly pre-stretched DEA roll for lifting a ten-fold payload its weight remains challenging. The keys to the successful development of stronger DEAs are the lightweight reinforcement to support the high pre-stretch in the DEA membrane. Here, we have two kinds of reinforcements, namely the polyimide-film hoop/tube and ladder frame for the bicep and finger muscles separately. As such, the highly pre-stretched dielectric elastomeric membrane (made of VHB 4910 acrylic foam tape) can sustain high voltage and thus a high electric field for forceful actuation. This greatly increases the work density and thus enables lifting a payload of at least tenfold of the muscle's weight. This bionic robotic arm is made of dielectric elastomeric biceps and fingers (see Figure 1). Such a bionic arm with grippers is designed for the task of pick and place, as heavy as an apple. As shown in Figure 1(b-c), the arm lowers upon activation of artificial biceps, but flexes upon deactivation. The bionic biceps are a multi-segment roll of multilayered dielectric elastomer membranes wound free of a core; this electrostatic roll elongates upon voltage activation. After deactivation, the length of the passive roll retracts as shown in Figure 2. On the other hand, the normally close gripper was activated to open but close (picking an apple) upon deactivation as shown in Figure 1d. The bionic finger is based on dielectric elastomer minimum energy structure; it extends upon voltage activation of DEA in it, but flexes back upon deactivation.

III. BIONIC BICEPS/TRICEPS

The movements of the human body are the resultant interaction between the muscles and the skeletal system. Muscular contractions bring the bones, to which the muscles are attached, into various actions. For example, the agonist-antagonist pair of biceps and triceps are responsible for the action of forearm lifting or lowering. When the biceps at the front of the upper arm contract for arm flexion, the triceps at the back relax. When the triceps contract for the arm lowering, the biceps relax. In order to imitate this arm movement, this work has a similar agonist-antagonist pair of artificial muscles made out of rolled dielectric elastomer actuators. They can produce a large strain with enough strength to lift a payload multiple times the muscle weight. They do not need the heavy gear as in traditional motor drives for speed reduction. Our bionic arm is simplified into a forearm linkage pivoted about the elbow to a vertical upper arm which was fixed and not moving. Two bionic biceps have the distal tendon attached in front of the elbow joint, but a bionic triceps attached to the rear of the elbow joint as shown in Figure 1(c)(d). Although the arrangement of DEA rolls is similar to the agonist-antagonist pair of biceps and triceps, DEA rolls elongate upon voltage activation unlike contraction of stimulated muscles. The DEA rolls recoil upon voltage deactivation.

A. Theory and Methods for Roll DEA

An activated DEA roll elongates as shown in Figure 2(a). For a quick estimate for the voltage-induced elongation, a DEA roll can be modeled using a dielectric elastomer tube, which was sandwiched by inner and outer compliant electrodes of negligible stiffness. Consider a dielectric elastomer tube of length L, radius R, and wall thickness t. Application of the voltage across the tube wall induces the electrostatic pressure:

$$p_e = \frac{1}{2}\varepsilon_r \varepsilon_0 \left(\frac{V}{t}\right)^2 \tag{1}$$

to squeeze the tube walls thinner. In the meantime, the tube is subjected to the boundary condition of zero hoop strain. Solving the linear Hookean constitutive law at the given loading and boundary conditions, the axial strain of the activated dielectric elastic tube is derived as:

$$\frac{\Delta L}{L} = \left(v + v^2\right)\frac{p_e}{E} \tag{2}$$

where E and v are the elastic modulus and Poisson's ratio respectively of this dielectric elastomer.

Materials available for dielectric elastomer include silicone, SEBS plastic film, or 3M VHB tape; whereas, compliant electrode materials include graphite powder, conductive carbon ink. Here, we chose 3M VHB 4910 as the dielectric elastomer material and graphite powder as the compliant electrode material. Fabrication of a DEA roll follows Figure 2(b). A flat dielectric elastomer membrane was first pre-stretched biaxially on the support of a rigid frame before being applied with compliant electrodes and polyimide hoop reinforcement strips. Next, the electrode membranes were laid with copper leads and stacked up like a multilayered capacitor. Rolling the stacked capacitor onto a pair of glass tubes yields a multilayered DEA roll. The weight of the bionic biceps made in this article is only 6.6g as shown in Figure 2(c). As the wound roll consists of multiple layers, it can carry much more load than a single-layer tube.

B. Tested Performance of Roll DEA

First, a bionic biceps (DEA roll) is subjected to a mechanical tensile test using Cometech QC-508M2F. As shown in Figure 3(a), it was mounted to the tensile tester. It started with a 4 times axial pre-stretch before being further stretched at a speed of 0.1mm/sec until 20% more than the pre-stretched length. The tension requirement increases with increasing the sample length. As the gradient to the tension-stretch relationship, the stiffness of the DEA roll was determined to be 97.5N/m. The tension-stretch relationship upon recoil is nonlinear due to the stress relaxation effect, which takes more time to settle.

Figure 3(b) shows the isometric test setup for characterizing a DEA roll. Then, the rolled actuator was fixed to the two stationary clamps of a tensile tester. Activation of the actuator does not change the length but lateral deformation. Then, the induced electrostatic pressure reduces the internal stress and thus

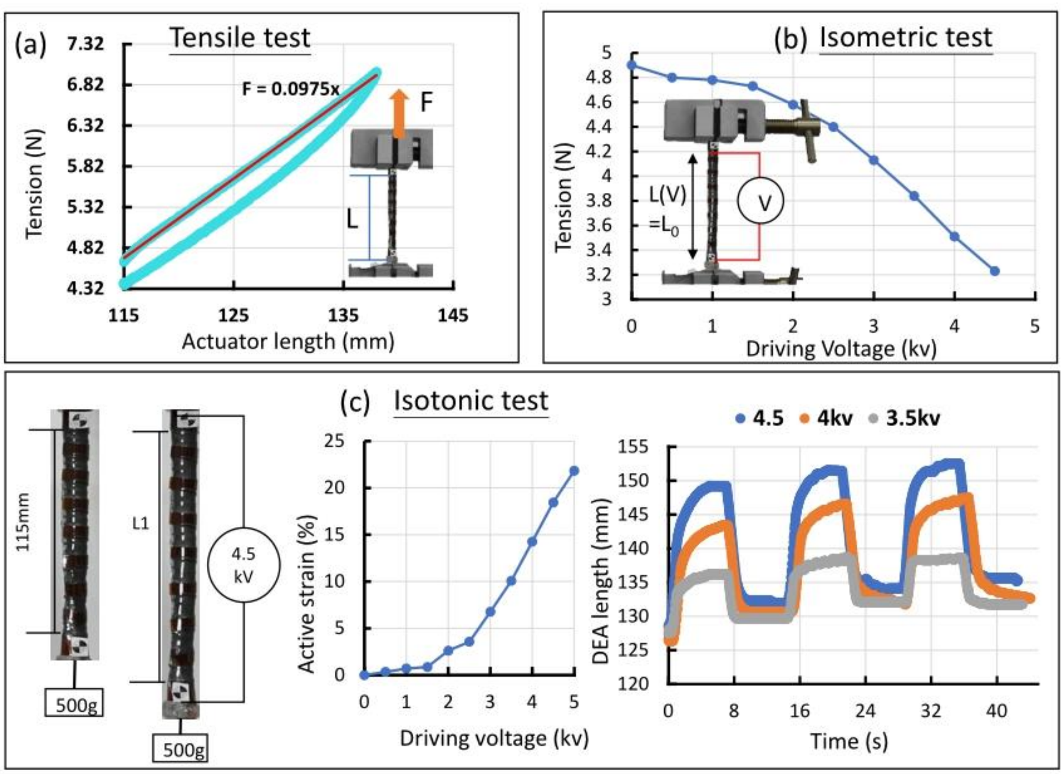


Fig. 3. (a) Tensile testing, (b) isometric and (c) isotonic actuation for a DEA roll

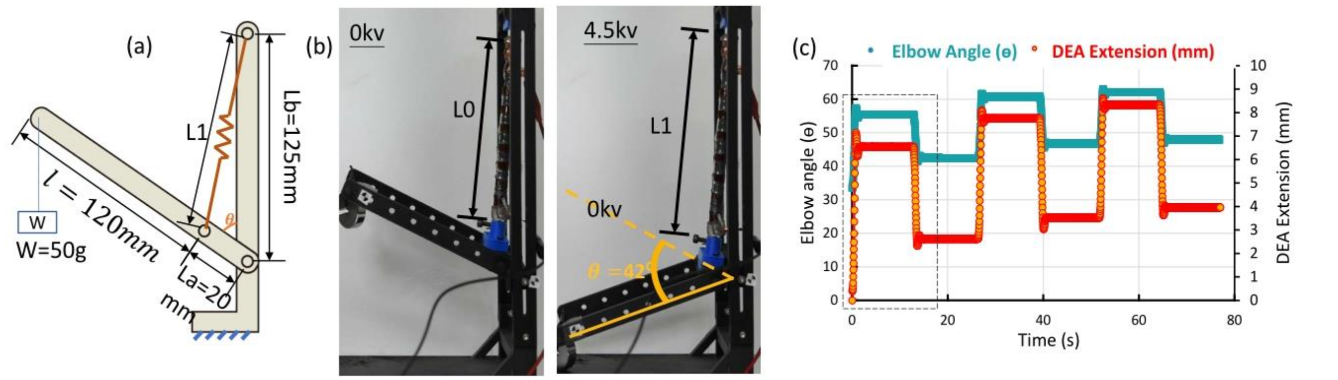


Fig. 4. Demonstrator of a bionic robotic arm: (a) simple model; (b) Activation for arm extension; (c) time response

relaxes the axial tension below pre-tension. Hence, the axial tension or blocked force in the DEA roll decreased with increasing the activation voltage.

Figure 3(c) shows the isotonic test setup for characterizing a DEA roll of 6.6gram and 115mm long. In the test setup, the roll was fixed to a bracket at one end but axially pre-stretched 4 times by carrying a 500-gram payload on the other end. This rolled actuator born a payload of 75 times heavier. Upon voltage activation, the DEA roll elongated and thus lowered the payload. It recoiled and returned to its original length upon deactivation. The recoil behavior of the rolled DEA is similar to that of a stretched rubber band. Figure 3(c) showed the maximum axial actuation achieved by the DEA roll is 21mm displacement, equivalent to 21% axial under 4.5kV activation. By excluding the hoop length, the active strain in the rolled DEA membrane is even higher. When the actuator was switched on and off, its pulsed response was measured. This leads to the determination of the rise time constant of 2.73s and fall time constant of 1.5s (which response to the 90% to the displacement step).

This isotonic test also yielded an important measure of work density or mass-specific work done, which is defined as the product of payload weight $m_{load}g$ and actuation displacement ΔL_{act} divided by the actuator mass m_{act}.

$$\text{work density} = \frac{m_{load}\, g \times \Delta L_{act}}{m_{act}} \qquad (3)$$

According to the measurement and equation, this DEA roll can delivered a work density of 15.3J/kg, which is only a fraction of the stored elastic potential energy in the highly pre-stretched elastomeric membranes.

In comparison, a spring roll [16] of dielectric elastomer actuator has similar construction like this work but having an internal spring core. It has a VHB 4910 membrane axially pre-stretched for 5 times and wound about a metallic helical spring. The spring roll [16] was reported of comparable active strain at a very high electric field of 109MV/m. However, its isotonic actuation for weight lifting is subpar, achieving merely 3.92 J/kg due to the added mass and stiffness from the spring core.

C. Demonstrator of a bionic robotic arm

Here, we have a simple demonstrator of a robotic arm (see Figure 4) which consists of an upper arm fixed vertically and a lower arm movable about the elbow joint. While the distal end of the lower arm is loaded with a deadweight, the proximal end is supported by two strands of artificial biceps. When the inactive artificial biceps extends to counter the tip load, there is a moment balance about the elbow joint between the elastic force F and the load W following:

$$W(l + L_a)\sin\theta = FL_a \cos\alpha \qquad (4)$$

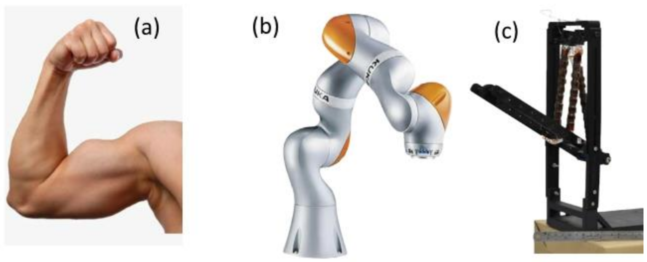
where θ is the elbow joint angle, and α is the angle between the lower arm and the normal to the bicep muscle strand. This suggests the lift strength at the hand (i.e. the tip of the lower arm) is only a fraction of the muscle tension F.

When activated, the artificial biceps will further elongate and thus lower the tip of the lower arm. This in turn extends the two-linkage arm with an increased elbow joint angle θ. The elbow joint angle can be determined using the cosine rule for a triangle formed by the upper arm length L_b, a proximal segment length L_a of the lower arm, and the bicep muscle length L_1. The active angle is derived as:

$$\theta = \cos^{-1}\left(\frac{L_a^2 + L_b^2 - L_1^2}{2L_aL_b}\right) \qquad (5)$$

This equation suggests that voltage-induced elongation in the artificial biceps will increase the elbow joint angle for arm extension.

This demonstrator of a robotic arm was driven by artificial biceps and triceps. The forearm weighs 59.8 grams and the tip deadweight is 50 grams (exclusive grippers). Three strands of DEA rolls (two biceps and one triceps) weigh 19.8 grams in total. The arm was initially flexed at an angle of 56 degrees. When the biceps was activated by 4.5kV, the arm extended to a new angle of 98 degrees. In short, the 4.5kV activation of the biceps caused the elbow joint an angle increment by 45 degrees at 4.5kV activation. Switching off of the biceps leads to bicep contraction (by recoil) and thus achieved the arm flexion again but at an increased angle (not back to the initial angle) due to the creep in artificial biceps. After a few cycles of arm extension and flexion, the recoil flexion angle settles to a steady-state angle. So, do the passive length of artificial biceps. This suggests that an active length measurement, possibly by direct capacitance measurement, is necessary for the position control of the robotic arm using dielectric elastomer actuators.



	Arm weight (kg)	Max. payload (kg)	Degree of Freedom	Angle range	Payload per arm mass (kg)
Human arm	3.7	15	7	80°	4.054
KUKA Robotics [x] LBR iiwa 7 R800	22.3	7	7	170°	0.314
This work	0.387	0.12	1	56°	0.466

Fig. 5. Comparison among a human arm, a lightweight robotic arm under motor drive6, and our bionic robotic arm using dielectric elastomer

Table in Figure 5 compares the payload capacity among an adult human arm, a motor-driven 'lightweight' robotic arm, and our bionic robotic arm using a dielectric elastomer actuator. In terms of the total weight, our DEA-based bionic robotic arm with one degree of freedom is the lightest in weight, which was primarily contributed by the arm structures and base. The three strands of DEA-based artificial muscles only contributed to 19.8gram out of the total arm mass of 295 grams. However, these lightweight DEA biceps each can carry a payload of 500gram. The arm leverage reduces the payload capacity by the DEA muscles to between 50 to 70 grams. In short, the payload capacity of this bionic robotic arm is about 0.466 of the arm weight, but 75 times the DEA muscles' weight. This suggests that the increased number of muscles will further help increase the payload capacity. In comparison, the 'lightweight' robotic arm developed by Kuka Robotics [6] with 7 degrees of freedom can only carry a payload of about one-third the arm weight. Among the three, an adult human arm of 3.7kg can carry 4 to 5 times the arm weight.

IV. BIONIC FINGERS AND GRIPPERS

As shown in Figure 6, a DE finger acts like a thumb. Its initial inactive posture curled backward, while the active posture extended. The anatomy of the DE finger bears a close similarity to the thumb. A flexible load beam acts a the phalanx, a DEA acts as the intrinsic muscle, and the polyimide frame acts as the tendon hood. The initial bent state in the inactive DE finger is due to the balance between the load beam's elastic force and the DEA's pretension. The negative tension acts on the flat load beam and thus bends the latter into a curved shape like a stretched bowstring bending the bow. The voltage activation of DEA in the finger reduces the negative tension and thus extends the previously flexed finger, as shown in Figure 6(a). The total weight of the gripper mechanism composed of three DE fingers is about 18g, but it can grip an apple weighing about 181.6g, which is 10 times its weight. The jaw opening and closing distance are nearly 50mm; the initial closing distance is 33mm, and the opening distance under high voltage is 83.3mm.

A. *Theory and Methods for DEA finger*

In the design of dielectric elastic finger, a tendon hood of polyimide frame was introduced to the intrinsic muscle, i.e. multilayered DEAs and the phalange based on a polyvinyl chloride load beam. This tendon hood helps to elevate the DEA membranes to a roof shape, thereby enlarging the moment generation about the load beam plane given the pre-tension in

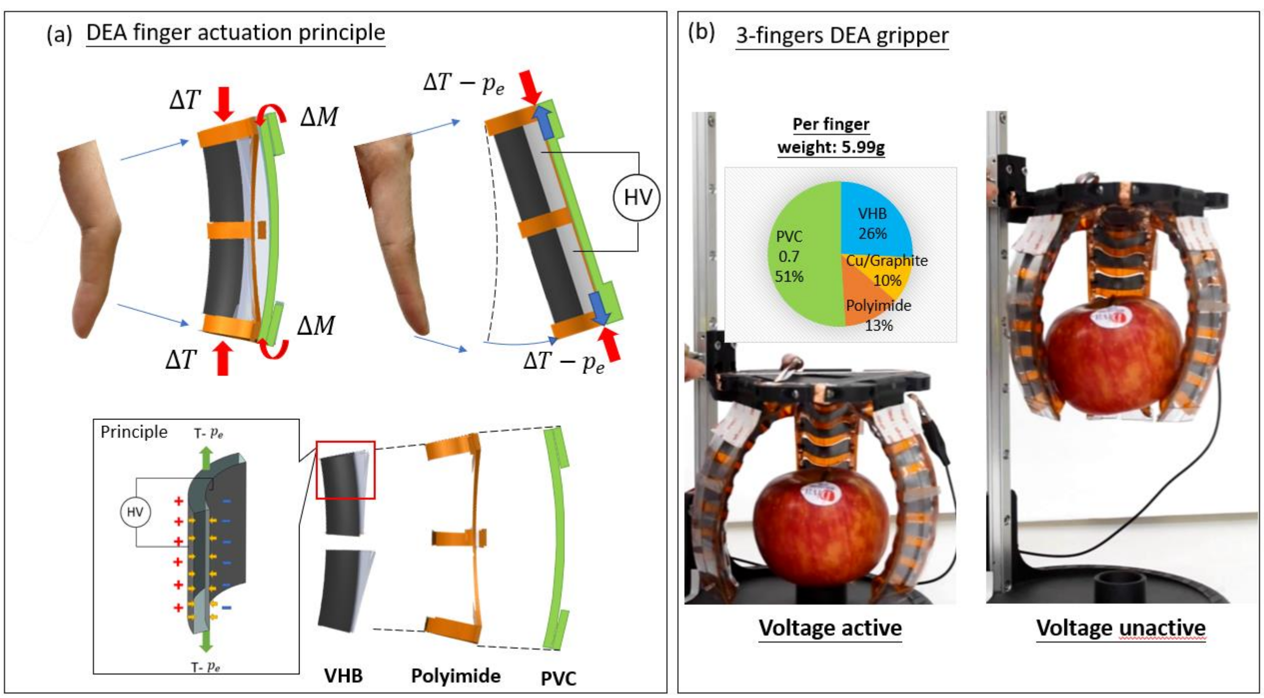


Fig.6. Bionic soft grippers: (a) working principle of dielectric elastomer fingers (b) demonstration of three normally closed grippers for picking an apple 10 times the gripper's weight

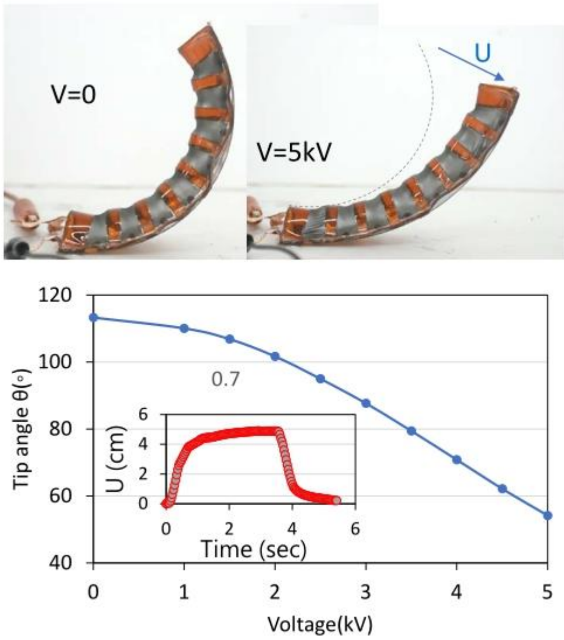


Fig. 7. Response of dielectric elastomer finger to activation (top) Shape change due to 5kV activation; (bottom) voltage-induced unbending and the time response due to pulsed activation.

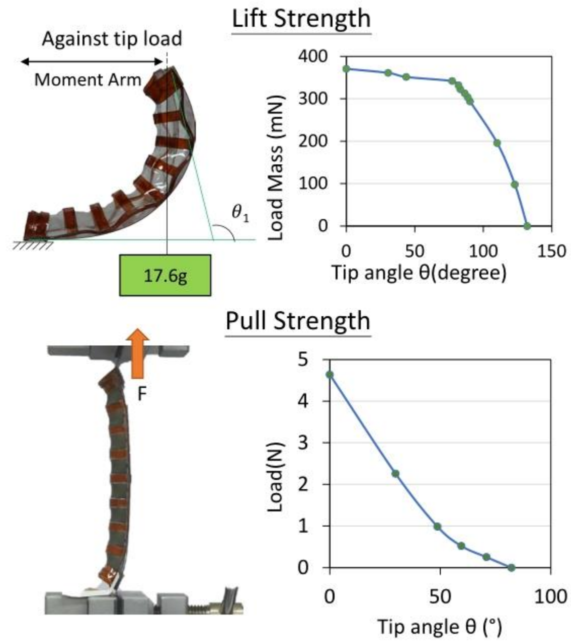


Fig. 8. Strength test: (top) lift strength in the finger swing direction; (bottom) pull strength nearly perpendicular to the finger swing direction

DEA. Under the action of electrostatic pressure p_e, the activated membrane expands and reduces in membrane tension. Given the tension center at a height h above the bending load beam, the voltage modulated bending moment reduces the following:

$$M(V) = h\left(T_0 - c \times p_e(V) A_c\right), \tag{6}$$

where A_c is the cross-section area of the multilayered DEA membranes and c is a fraction of axial force transmission with respect to the electrostatic compressive force. According to Hooke's law, the load beam will undergo an elastic bending following:

$$\Delta\theta(V) = \theta_0 - \theta(V) = \frac{(T_0 - T(V))h}{k_\theta}, \tag{7}$$

where k_θ is the flexural stiffness of the load beam.

How do you shape a multi-segment dielectric elastomer minimum energy structure into a hood with an elevated height above the base of load beam? This multi-segment DEMES is made of a highly pre-stretched DEA multilayers bonded onto a flimsy ladder- like polyimide frame. Release of such flimsy DEMES ends up with a crumpled roll that buckles longitudinally under high negative tension. Interestingly, the DEMES flanges can be spot glued to the narrow side of a stiff base and thus buckled transversely into a tendon hood with multiple bridge structures. Such buckled tendon bridges are shape with the outer profiles of disks that rotates with the back spine, i.e. the stiffer base of load beam.

B. Finger actuation and strength

Like a thumb-up posture, an inactivated DEA finger bends in a backcurve. Activation of the DEA reduces the pre-tension and thus unbends the load beam. Figure 7 shows the voltage unbending test of a DEA finger, which was cantilevered at the root. During the test, the driving voltage was ramped up stepwise from 0kV up to the electrical breakdown voltage, at a voltage step of 0.5kV if there were no electrical breakdown. Then, photographs of the activated finger were taken one second before the next voltage step. Image processing yields the activated tip bending angle with respect to the anchored root. The tip bending angle decrease with increasing voltage following the one minus a quadratic function as predicted by Equation (7). Subsequently, pulsed activation of the DEA finger yields the time response. The activated DEA finger swept a 60-degree stroke with 50mm tip displacement. The 90% rise time for voltage-induced unbending takes 1.2 seconds while the 90% fall time for recoiled bending is shorter at 0.67 seconds.

Next, the 6-gram DEA finger was subjected to the lift and pull tests. The lift test has the cantilevered DEA finger subjected to tip loading near the finger swing direction. The lift test was done by loading the fingertip with an increasing number of paper clips (each of 0.49-gram mass) until the curled finger was unbent to collapsing position. The maximum load applied at the critical point of collapse is then the lift strength of the finger as shown in Figure 8. The pull test has the DEA finger stretched by a tensile tester; the finger sample were mounted the tensile tester while its movable end was pulled at a rate of 0.1mm/sec until the finger being straightened. The pulling force was measured throughout stretching. The experiment shows the lift strength in the finger swing direction is merely 38.2-gram force while the pull strength nearly perpendicular to the finger swing direction is as great as 470gram. This suggests that the fingers should be positioned perpendicularly to the swing position for maximum payload, just like a hook.

Last but not least, the DEA-based bionic finger was compared with the commercial adaptive robot gripper in terms of payload capacity. Table 2 shows that the DEA grippers of 18 gram can carry a payload 10 times the grippers' weight. In comparison, the larger commercial robotic grippers can generate much larger blocked force of 30-70N, but its payload capacity is comparable to its weight.

Table 1. Comparison between hard and soft grippers

Parameters	Adaptive robot gripper [22]	DEA grippers (This work)
Gripper opening	1 to 155 mm	0 to 101mm
Gripper weight	2.3kg	18gram
Grasped object diameter	20 to 155 mm	20 to 101 mm
Maximum payload	2.5kg	180g

V.CONCLUDING REMARKS

A long roll of the actuators has strain accumulated at the expenditure of reduced strength. This work introduced hoop reinforcement and multi-segmentation to a long roll of dielectric elastomer actuator and thereby resolve the problem of keeping high membrane pre-stretch and high dielectric elastomer strength. These polyimide hoop reinforcements add little weight as compared to other components. The lightweight hoop reinforcement helps the rolled DEA to sustain a higher electric field and thus produce high active stress to do work.

The multi-segment roll of 4-layered DEA was pre-stretched by 5 times in the hoop direction and 4 times in the axial direction. The segmented roll DEA thus sustained a very high electric field of up 105MV/m. Such DEA rolls each of 6.6-gram light and 115mm long supported a 500gram payload at the 4 times axial pre-stretch when not activated. When activated between 4kV to 5kV, the DEA roll produced 24-25% elongation. Hence, this reinforced actuator achieved the 15.3J/kg isotonic work density, comparable to human muscles. The reinforced DEA hopefully can be made even stronger by multiplication. Besides addressing the need for the bionic robotic arm, the forceful drive will find applications to mobile robots that execute bioinspired locomotion such as running and jumping on unstructured terrains.

REFERENCES

[1] S. Popic and B. Miloradovic, “Light weight robot arms-an overview,” INFOTEH- JAHORINA 14 (2015)
[2] E. Robotics, “Elephant robotics expands lightweight robot arm product line,” (2021).
[3] J. P. Whitney, M. F. Glisson, E. L. Brockmeyer, and J. K. Hodgins, “A low-friction passive fluid transmission and fluid-tendon soft actuator,” in 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IEEE, 2014) pp. 2801–2808
[4] E. Guizzo, “Disney robot with air-water actuators shows off ”very fluid” motions,” (2021)
[5] R. K. Katzschmann, A. De Maille, D. L. Dorhout, and D. Rus, “Cyclic hydraulic actuation for soft robotic devices,” in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE, 2016) pp. 3048–3055
[6] Lbr iiwa, [Online]. Available: https://www.kuka.com/ende/products/robot-systems/industrial-robots/lbr-iiwa
[7] R. Allain, “How much energy can you store in a rubber band?” (2018)
[8] R. E. Pelrine, R. D. Kornbluh, and J. P. Joseph, “Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation,” Sensors and Actuators A: Physical 64, 77–85 (1998).
[9] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, “High-speed electrically actuated elas-tomers with strain greater than 100%,” Science 287, 836–839 (2000)
[10] G. Kovacs, P. Lochmatter, and M. Wissler, “An arm wrestling robot driven by dielectric elastomer actuators,” Smart Materials and Structures 16, S306 (2007)
[11] T. Lu, Z. Shi, Q. Shi, and T. Wang, “Bioinspired bicipital muscle with fiber-constrained dielectric elastomer actuator,” Extreme Mechanics Letters 6, 75–81 (2016) [12] C. G. Atkeson and S. Schaal, "Robot learning from demonstration," in *ICML*, 1997, vol. 97: Citeseer, pp. 12-20.
[12] M. Duduta, E. Hajiesmaili, H. Zhao, R. J. Wood, and D. R. Clarke, “Realizing the potential of dielectric elastomer artificial muscles,” Proceedings of the National Academy of Sciences 116, 2476–2481 (2019)
[13] “The eap/human armwrestling match.” [Online]. Available: https://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-armwrestling.htm
[14] G. Kofod, P. Sommer-Larsen, R. Kornbluh, and R. Pelrine, “Actuation response of poly- acrylate dielectric elastomers,” Journal of intelligent material systems and structures 14, 787–793 (2003).
[15] S. Ashley, “Artificial muscles,” Scientific American 289, 52–59 (2003).
[16] Q. Pei, M. Rosenthal, S. Stanford, H. Prahlad, and R. Pelrine, “Multiple-degrees-of- freedom electroelastomer roll actuators,” Smart materials and structures 13, N86 (2004)
[17] J. Huang, T. Lu, J. Zhu, D. R. Clarke, and Z. Suo, “Large, uni-directional actuation in dielectric elastomers achieved by fiber stiffening,” Applied physics letters 100, 211901 (2012).
[18] G.-K. Lau, H.-T. Lim, J.-Y. Teo, and Y.-W. Chin, “Lightweight mechanical amplifiers for rolled dielectric elastomer actuators and their integration with bio-inspired wing flappers,” Smart Materials and Structures 23, 025021 (2014)
[19] T.-G. La, G.-K. Lau, L.-L. Shiau, and A. W.-Y. Tan, “Muscle-like high-stress dielectric elastomer actuators with oil capsules,” Smart materials and structures 23, 105006 (2014).
[20] G.-K. Lau, D. D.-T. Tan, and T.-G. La, “Large axial actuation of pre-stretched tubular dielectric elastomer and use of oil encapsulation to enhance dielectric breakdown strength,” Smart Materials and Structures 24, 045025 (2015)
[21] S. Rosset and H. R. Shea, “Small, fast, and tough: Shrinking down integrated elastomer transducers,” Applied Physics Reviews 3, 031105 (2016)
[22] ROBOTIQ, “3-finger adaptive robot gripper,” (2020), https://robotiq.com/products/ 3-finger-adaptive-robot-gripper [Online: January 1, 2020.]

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